IMPROVING QUALITY

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INCREASING THE QUALITY OF TEMPERED GLASS ON AN OPERATING PROCESS LINE

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Models describing the dependence of the shape of glass on the tempering regime are developed. Simulation of the algorithm controlling the tempering of automobile glass is performed. It is shown that the quality of the glass produced can be further improved. The effectiveness of using simulation in developing corrective actions in the production of tempered glass is validated.

Key words: tempered glass, shape, simulation, regime.

The technological process of tempering glass is conducted on a horizontal continuous flow facility. Glass blanks are heated in a four-chamber tunnel furnace and then pressed to impart a prescribed shape to the glass. Next the glass with the prescribed shape is tempered by rapid cooling in an air stream. After tempering the glass is slowing cooled.

The glass must meet stringent requirements with respect to tolerances with respect to deviation of curved articles from a prescribed shape. The shape and dimensions of curved articles are checked with a control template [1]. The gap between the edge of the glass and the contour of the template (lack of fit) on four sides $A – B$, $B – C$, $C – D$, and $D – F$ must not exceed a prescribed amount. The transverse curvature is also checked according to the deviation of the generatrix of the line of a cylindrical surface.

Statistical analysis of the measurements of the shape of glass has revealed a substantial variance in the lack of fit and the deviation of the generatrix line. The coefficient of variation varies over wide limits from 33 to 44%, which characterizes the low accuracy of the technical process.

The relation between the lack-of-fit measurements on the sides of the glass and the deviation of generatrix of the line of the cylindrical surface was analyzed. The closeness of the relation between the measurements was evaluated using the pair correlation coefficients (Table 1).

The values of the computed correlation coefficients presented in Table 1 show a weak relation between the lack-of-fit measurements on the sides of the glass and the deviation of the generatrix of the line of a cylindrical surface. This makes it possible to use a system of independence equations to describe the shape of the tempered glass.

More than 20 regime variables of the tempering process were considered as influential factors in constructing models. It was important to determine the effect of the configuration and dimensions of the glasses produced on the shape deviation. This problem was solved using dispersion analysis. The measurements of shape deviations of large-size 760 × 600 mm (left and right) as well as small size 686 × 526 mm (left and right) side automobile glass were used for the analysis. The size of the sample used for the analysis was 313 measure-

TABLE 1. Matrix of Pair Correlation Coefficients

	y_4	y_5	y_6	y_7	y_8
y_4	1.00	0.06	0.02	0.30	0.15
y_5	0.06	1.00	0.31	0.33	– 0.01
y_6	0.02	0.31	1.00	0.15	– 0.22
y_7	0.30	0.33	0.15	1.00	– 0.18
y_8	0.15	– 0.01	– 0.22	– 0.18	1.00

Notations: y_4) lack of fit on the side $A – B$ of the glass; y_5) lack of fit on the side $B – C$; y_6) lack of fit on the side $C – D$; y_7) lack of fit on the side $D – F$; y_8) deviation of the generatrix of the line of a cylindrical surface.

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ments. The large-size glass is produced on the facility in one flow and the small size glass is produced in two flows, i.e., two glass blanks are produced in parallel. In the analysis the configuration of the glass, determined by the glazing side, was coded by numbers: left glass — 0, right glass — 1. The number of flows of the loaded glass blanks depends on the size of the blanks, so that the numbers 1 and 2 were used to code the large- and small-size, respectively, glass.

Dispersion analysis made it possible to determine the effect of the configuration of the glass on the deviation of the generatrix of the cylindrical surface as well as the effect of the dimensions of the glass on the magnitude of the lack of fit and the deviation of the generatrix of the line. For this reason, the configuration and the dimensions of the articles being made were included as influential factors, together with the regime variables, in the structure of the models being developed.

The experimental data were used to develop a system of independent regression equations which describes the effect of the tempering regime on the deviation of the shape of the glass:

$$y_4 = 13.6 - 1.82x_{12} + 0.03x_{19} - 0.25x_{22};$$

$$y_5 = 20.9 - 0.012x_6 - 1.68x_{12} - 3.9x_{15} - 1.5x_{17} + 0.06x_{19} - 0.42x_{22};$$

$$y_6 = 2.34 - 0.021x_8 + 0.019x_{10} - 0.31x_{13};$$

$$y_7 = -3.1 + 0.019x_4 - 0.012x_6 + 3.14x_{18} - 0.16x_{22};$$

$$y_8 = -2.05 - 0.009x_6 + 0.013x_7 + 0.0032x_9 - 1.79x_{17} + 2.07x_{18} + 0.057x_{19} - 0.013x_{20} - 0.389x_{22}, \quad (1)$$

where x_4 is the dome temperature in the chamber 1 according to the center of the zone 1; x_6 is the dome temperature in the chamber 2 in zone 2; x_7 is the bottom temperature in the chamber 2 in the zone 12; x_8 is the dome temperature in the chamber 3 according to the center of zone 1; x_9 is the bottom temperature in the chamber 3 in zone 11; x_{10} is the dome temperature in the chamber 4 in the zone 2; x_{12} is the speed of the conveyer in the furnace; x_{13} are the dimensions of the glasses produced, determined by the number of flows of blanks on the conveyer; x_{15} is the slowing of the rollers at the entrance to the press; x_{17} is the pressing regime, left interval 1; $x_{18}$is the pressing regime, left interval 2; x_{19} is the rise height of the punch; x_{20} is the pressure of the air fed from above for precooling of the pressed glass; and, x_{22} is the configuration of the glass determined by the glazing side.

The coefficients of the models developed are small. The computed values of the F criterion is greater than the tabulated value for significance level 0.05, which confirms the dependence of the coefficients of determination which were obtained, i.e. it shows the existence of a stochastic relation between the resultant and influential factors.

The accuracy of the regressions model (1) is low. To increase the accuracy the parameters of the models were determined more accurately during operation. The accuracy of adaptive models was estimated according to the magnitude of the coefficient of the pair correlation between the actual data and the data obtained from the models (Table 2). The larger the value of the correlation coefficient, the more accurately the model describes the character of the changes in the resultant variable.

TABLE 2. Accuracy of Adaptive Models (1)

Resultant variable y	Maximum standard deviation, mm	Maximum absolute error of the model, mm	Correlation coefficient
y_4	0.53	1.4	0.53
y_5	0.68	1.7	0.07
y_6	0.40	1.4	0.72
y_7	0.56	1.3	0.50
y_8	0.50	1.04	0.53

The adaptive models developed can be used to develop corrective actions in quality management systems in the production of tempered automobile glass.

Computer modeling of the glass production process plays an important role in improving the control of the technological processes in the production of automobile glass [2]. The use of simulation for evaluating the efficiency of the control of the technological process of the production of automobile glass and to generate proposals to improve the control algorithms is examined below.

The experimental data on the input and output variables collected from an object were used for simulation. The experimental data make it possible to evaluate the accuracy of the correspondence between the behavior of the model and the behavior of the real object and, if necessary, to adjust the parameters of the model and evaluate the effectiveness of the control algorithms used as compared with conducting the process manually with the same initial data.

Let us examine the problem of optimal control of the technological process of tempering. The control criterion adopted is the additive convolution of the deviations of the shape of the glass along the perimeter and the deviation of the generatrix of the line of the cylindrical surface. The control problem was formulated as follows:

to minimize the criterion

$$K = C_4 \left| y_4 / y_{4\max} \right| + C_5 \left| y_5 / y_{5\max} \right| + C_6 \left| y_6 / y_{6\max} \right| + C_7 \left| y_7 / y_{7\max} \right| + C_8 \left| y_8 / y_{8\max} \right| \quad (2)$$

while satisfying the constraints imposed on the range of variation of the regime variables determined by the technological rule

$$x_{n,\min} \le x_n \le x_{n,\max} \quad \text{for } n = 1, 2, ..., 22. \quad (3)$$

In Eq. (2) the lack of fit of the sides of the glass to the template and the deviation of the generatrix of the line of a cylindrical surface are normalized by dividing the indicators by their admissible (maximum) value. The weights of the

TABLE 3. Variation Range of Regime Variables During Modeling

Regime variable	Coded value	Minimum value	Maximum value	Variation step size
Dome temperature in chamber 1 according to the center of zone 1, °C	x_4	555	585	2
Dome temperature in chamber 2 in zone 2, °C	x_6	575	605	2
Bottom temperature in chamber 2 in zone 12, °C	x_7	560	590	2
Dome temperature in chamber 3 according to the center of zone 1, °C	x_8	660	665	2
Bottom temperature in chamber 3 in zone 11, °C	x_9	590	655	2
Dome temperature in chamber 4 in zone 2, °C	x_{10}	597	670	2
Cycle of parts loading into furnace, sec	x_{12}	6.8	7.2	0.012
Slowing of rollers, sec	x_{15}	0.18	0.25	0.004
Interval 1 left	x_{17}	0.25	0.45	0.015
Interval 2 left	x_{18}	0.30	0.45	0.01
Punch height 1, mm	x_{19}	7	25	1.5
Top pre-blow at air pressure, mm water	x_{20}	145	185	2.5

terms in the criterion are determined by adjusting the coefficients $C_4 - C_8$. The terms are taken on the basis of the modulus in order to prevent the sign of the deviation (+, –) from affecting the value of the criterion.

In solving the control problem (adjusting the operating regime of technological equipment), the type of article chosen, as characterized by the values of the factor variables x_{13} — the number of flows and x_{22} — the configuration of the glass, is assumed to be given.

The control problem consists in picking a tempering regime for which the criterion (2) assumes its minimum value. In the limit it equals zero, which happens when the values of the terms are zero. This is possible when articles are made precisely according to the template.

The search for the optimal regime was made by a numerical method using a coordinate-descent algorithm. The steps in the search using a regime variable (coordinate) were chosen so as to obtain the required computational accuracy and to decrease the number of iterations. The magnitude of the steps was no more than 10% of the admissible range of variation of the regime variables.

The modeling was conducted for values of the regime parameters that correspond to the range of the variation when the tempering process is conducted manually (Table 3).

The predicted quality indicators for the article made were determined by calculations performed using the adaptive models (1), describing the dependence of the lack of fit along the edges of the glass and the deviation of the generatrix of the line of a cylindrical surface from the tempering regime.

The admissible accuracy of the shape of the glass being produced in an optimal control tempering process is reflected in Table 4. For comparison, this table also shows the quality indicators obtained using manual control of the technological process.

As one can see from Table 4, the proposed control algorithm makes it possible to produce tempered glass of higher quality. The accuracy with which the glass is made is increased by decreasing the lack of fit to the template and the deviation of the generatrix of the line of the cylindrical surface. The average value and standard deviation of the measurements of the lack of fit and the deviation of the generatrix of the lines decrease.

The maximum lack of fit of the glass on the sides in individual measurements did not exceed 1.5 mm and there was virtually no deviation of the generatrix of the line of cylindrical surface. For a manual tempering process the lack of fit on the glass sides was 2.9 mm and deviation of the generatrix of the lines was 1.42 mm.

TABLE 4. Comparative Characteristics of the Articles with Optimal Control and with Manual Tempering

Glass characteristic	Modeling results		Manual process	
	average value	standard deviation	average value	standard deviation
Lack of fit on the side $A - B$, mm	0.52	0.31	1.15	0.51
Lack of fit on the side $B - C$, mm	0.27	0.26	1.36	0.52
Lack of fit on the side $C - D$, mm	0.11	0.26	1.12	0.48
Lack of fit on the side $D - F$, mm	0.92	0.24	1.42	0.52
Deviation of the generatrix of the line of a cylindrical surface, mm	0.006	0.01	0.38	0.35

TABLE 5. Comparison of the Glass Tempering Regime with Optimal and Manual Control of the Process

Regime variable	Coded value	Modeling results		Manual process	
		average value	standard deviation	average value	standard deviation
Dome temperature in chamber 1 according to the center of zone 1, °C	x_4	558	0	568	8
Dome temperature in chamber 2 in zone 2, °C	x_6	600	3	583	8
Bottom temperature in chamber 2 in zone 12, °C	x_7	576	7	575	7
Dome temperature in chamber 3 according to the center of zone 1, °C	x_8	651	9	628	15
Bottom temperature in chamber 3 in zone 11, °C	x_9	626	20	618	15
Dome temperature in chamber 4 in zone 2, °C	x_{10}	612	16	631	15
Cycle of parts loading into furnace, sec	x_{12}	7.2	0.012	7	0.048
Slowing of rollers, sec	x_{15}	0.24	0.006	0.22	0.018
Interval 1 left	x_{17}	0.36	0.05	0.37	0.06
Interval 2 left	x_{18}	0.32	0.018	0.39	0.043
Punch height 1, mm	x_{19}	10.4	2.7	15.2	6.1
Top pre-blow at air pressure, mm water	x_{20}	157	5.8	165	9.4

The shape accuracy for the glass being made with optimal control is increased by selecting a tempering regime and holding it more accurately at the computed level. Comparative data obtained for tempering regimes by modeling control algorithm for a manual process are presented in Table 5. It is evident from the table that the thermal regime of the horizontal furnace is adjusted negligibly, by no more than 4%. Appreciable corrections obtain for the following variables: punch height x_{19} — 32%; interval 2 left x_{18} — 18%; slowing of the rollers x_{15} — 9%.

Simulation showed that it is possible to increase further the quality of the tempered automobile glass produced in an operating production facility by optimizing the operating regime of the technological equipment.

The simulation procedure described above for the technological process can be successfully used in automobile-glass quality management systems by taking corrective actions to maximize customer satisfaction with the product quality.

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